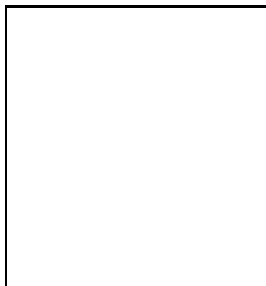


# EXTRA DIMENSIONS AND THE COSMOLOGICAL CONSTANT PROBLEM

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This article reviews the arguments why extra dimensions provide a unique opportunity for progress on the cosmological constant problem, and updates the status of – and the objections to (with replies) – the specific proposal using supersymmetric large extra dimensions (SLED).

## 1 Extra Dimensions and the Cosmological Constant Problem

For thirty years technical naturalness – the requirement that small parameters be stable against renormalization<sup>1</sup> – has been a major guideline for searches to replace the Standard Model. For instance, the observation that particles with mass  $M$  contribute to the Higgs potential an amount  $\delta V_H \propto M^2 H^* H$  leads to the Hierarchy Problem: how can  $M_w/M_p \sim 10^{-15}$  be technically natural if any particles at all have masses between  $M_w$  and  $M_p$ ? Naturalness would be assured if the Higgs were composite at a scale  $\Lambda_c \gtrsim M_w$  since then there is no potential for heavy particles to correct above the scale  $\Lambda_c$ . It would also be assured if the Higgs were elementary but supersymmetry, broken at scales  $\Lambda_s \gtrsim M_w$ , enforced the cancellation of bosons and fermions in their contribution to  $\delta V_H$ . Such considerations significantly shaped the design of the LHC, in order to test both of these proposals.

### Naturalness in crisis

Yet the discovery<sup>2</sup> that the universe is now entering an epoch of accelerated expansion has provoked an unprecedented angst<sup>3,4</sup> about the use of technical naturalness as a fundamental theoretical criterion. It does so because the acceleration is well described by adding a cosmological constant,  $\lambda$ , to Einstein's equations,

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \lambda g_{\mu\nu} = \frac{T_{\mu\nu}}{M_p^2}, \quad (1)$$

with the required constant much smaller than most other fundamental scales we know. Regarded as an energy density,  $\lambda = \rho/M_p^2$ , observations require  $\rho = \mu^4$ , with  $\mu \lesssim 10^{-2}$  eV.

Since particles of mass  $M$  contribute  $\delta\rho \propto M^4$ , the contribution of almost all known particles to  $\rho$  are already much too large: for electrons  $m_e^4/\mu^4 \sim 10^{36}$ , for the QCD phase transition  $\Lambda_{QCD}^4/\mu^4 \sim 10^{44}$ , while for electroweak bosons  $M_w^4/\mu^4 \sim 10^{56}$ . The contributions of particles with  $M \gg M_w$  are generically larger still, but can be suppressed (such as by supersymmetry) to contribute only  $\delta\rho \sim M_w^4$ .

This makes the cosmological constant (CC) problem the mother of all naturalness problems, since its roots lie with particles we already know rather than hypothetical particles having  $M \gg M_w$ . With naturalness as their guide, theorists unaware of accelerators operating above  $10^{-2}$  eV might confidently predict the discovery of supersymmetric partners split in mass from the electron by this scale, in order to solve the CC problem. How can we trust naturalness as a guide at the electroweak scale if it lets us down so badly on scales we thought we understood?

## How extra dimensions can help

The essence of the problem is that the Lorentz invariance of the vacuum implies that the vacuum stress energy satisfies  $T_{\mu\nu}^{vac} = -\rho g_{\mu\nu}$ , making  $\rho/M_p^2$  indistinguishable from  $\lambda$  in eq. (1). The puzzle is how the curvature of space (and so also  $\lambda$ ) can be as small as is measured when quantum corrections to  $\rho$  should be large.

Extra dimensions help by breaking the link between 4D Lorentz invariant energies ( $\rho$ ) and 4D curvature ( $\lambda$ ). They can do so because if the vacuum energy is associated with the tension of a surface (or brane), then it is localized (and not Lorentz invariant) in the extra dimensions. Although it necessarily curves spacetime, it sometimes does so by curving the extra dimensions and not the four dimensions we see.<sup>5,6,7</sup>

This is all very well, but any extra dimensional model becomes effectively four dimensional at energies below its Kaluza-Klein scale,  $\Lambda_{KK} \sim 1/r$ , where  $r$  denotes a generic linear size (radius) for the largest extra dimensions. Consequently an intrinsically extra-dimensional explanation of the size of  $\rho$  can only be useful if the extra dimensions are large:  $\Lambda_{KK}$  cannot be too much larger than  $\mu \sim 10^{-2}$  eV, so  $r$  can't be much smaller than  $\sim 10$   $\mu\text{m}$ . Remarkably, extra dimensions can actually be this large,<sup>8</sup> but only within a 'brane-world' scenario for which all observed particles are trapped on a 4D surface (or 3-brane). In this case only gravitational measurements probe the extra dimensions, and constraints on deviations from Newton's Law presently allow dimensions slightly smaller than 50  $\mu\text{m}$ .<sup>9</sup> Most encouragingly, large extra dimensions potentially do just what one wants: because observed particles are trapped on a brane, their non-gravitational properties are unchanged (as they must be) at the energies to which we have access. All that is modified is how their vacuum energy gravitates.

The extra-dimensional approach to the CC problem starts with this observation, and asks whether the theoretical elbow room thus opened is sufficient to allow a small enough 4D curvature in a technically natural way. This involves re-asking the cosmological constant problem in higher dimensions: What choices are required to make our observed 4 dimensions very flat? And can these choices be stable against renormalization? So far these issues are most thoroughly explored in 6 dimensions, to which we now turn.

## 2 Supersymmetric Large Extra Dimensions (SLED)

The best-developed proposal along these lines is the SLED proposal,<sup>7,10,11,12</sup> according to which all known particles are localized on one of possibly many (usually two) parallel 3-branes that are situated at points within a 6D spacetime whose two extra dimensions are at present imagined to be  $r \sim 10$   $\mu\text{-metres}$  in size, so that  $1/r \sim 10^{-2}$  eV is not so different from  $\mu$ . It is further assumed

that the ‘bulk’ physics – not trapped on the branes – is supersymmetric, and so is described by any one of the many known 6D supergravities. If the extra dimensions are not too strongly warped (as is true for the majority of explicit solutions known<sup>13,10</sup>) the 4D Planck mass is of order<sup>8</sup>  $M_p \sim M_g^2 r$ , so the scale of the 6D Newton constant must be  $M_g \sim 10$  TeV. The bulk supersymmetry is imagined to be badly broken by the branes, whose tension is imagined to be of the order of (but somewhat smaller than)  $M_g$ .

This proposal is the best developed in several senses. First, it is the one for which the naturalness issues have been the most thoroughly explored.<sup>14,15,16,17,18</sup> Second, it is (so far) the only extra-dimensional framework that does not argue for a vanishing 4D curvature, but instead provides an explicit mechanism for a nonzero 4D curvature of size  $\mu$ . Finally, it leads to a known low-energy 4D field theory within which gravity is described by a scalar-tensor system, with the scalar labelling the classical flat direction corresponding to overall re-scalings of the extra dimensions, within which a realistic quintessence-type accelerated expansion can plausibly take place.<sup>19,20,21</sup>

Best of all, the extra dimensions themselves must be very large,  $1/r \sim \mu$ , and the scale of gravity in the extra dimensions must be low,  $M_g \sim 10$  TeV. As a result the proposal is unusually predictive — with many testable predictions for tests of gravity and for particle colliders,<sup>22</sup> in addition to its implications for cosmology.

## 2.1 Where we stand

The SLED proposal involves re-asking the CC problem in higher dimensions. This comes in two steps: (i) enumerate the choices which are required to obtain a small 4D curvature within a particular extra-dimensional context; (ii) identify whether or not these choices are stable against renormalization (and so are technically natural).

### What is required for 4D flatness?

Most of the progress so far has been in identifying what choices are required for matter on the branes in order to obtain compactifications whose 4D geometry is approximately flat. Although it is not crucial for the naturalness arguments, these choices are best explored within chiral gauged 6D supergravity.<sup>23</sup> Although not the simplest, this supergravity receives special attention because it allows spherical compactifications, and so can involve only positive-tension branes.<sup>24,7,10,13</sup> Spherical extra dimensions are related to positive-tension branes by a topological argument, which is easiest to see for branes whose tension,  $T_b$ , back-reacts on the geometry to give a conical defect, with defect angle  $\delta_b = T_b/M_g^4$  (so  $\delta_b/2\pi = 4GT_b$ ). The Euler number,  $\chi$ , for the extra dimensions then is

$$\chi = 4G \sum_b T_b + \frac{1}{4\pi} \int d^2x \sqrt{g} R_2, \quad (2)$$

where  $R_2$  is the 2D geometry’s Ricci scalar. Notice that for toroidal compactifications  $R_2 = \chi = 0$ , so the brane tensions must all sum to zero (and some in particular must be negative). On the other hand, for spherical compactifications  $\chi = 2$ , so all of the tensions can be positive.

A broad class of exact solutions to 6D gauged, chiral supergravity are now known, including those which are 4D flat,<sup>7,10,13,18</sup> those having curved 4D maximal symmetry<sup>15</sup> and those which are time-dependent.<sup>16</sup> These show that solutions appropriate to two source branes are generically time-dependent, describing geometries wherein the extra dimensions implode or run away to flat 6D space. It turns out that for codimension-two branes a sufficient condition that ensures that all static solutions are 4D flat is to have the branes not couple to the 6D dilaton (a scalar which is partnered to the graviton by 6D supersymmetry).<sup>10,16</sup>

## How stable are these choices?

The next question asks how stable are the choices required to make the observed 4 dimensions flat. This question comes in two separate parts: (i) are the choices required for couplings in the action stable against renormalization; and (ii) given specific choices for the action, are acceptable solutions stable against changes to the initial conditions.

*Stability to initial conditions:* Given the number of solutions now known it is clear that, even given appropriate brane properties, the generic solutions to 6D supergravity describe time-dependent runaways.<sup>16</sup> This shows that extra dimensional approaches to the CC problem generically have an initial condition problem: they describe the universe around us only if the universe starts out in a particular way. This makes them like the Hot Big Bang model itself, whose similar initial-condition problems inspired the invention of inflationary scenarios. Since the plausibility of initial conditions for the later universe can potentially be addressed by changing the dynamics of the earlier universe (such as through inflation), this kind of initial-condition problem is a price worth paying if it allows progress to be made on the more difficult issue of technical naturalness.

*Stability to renormalization:* The key question is whether the choices which allow 4D flat solutions are natural, in the sense of being stable against renormalization. Once arranged as desired, do these choices stay made as heavy particles are integrated out? Although work along these lines is still in progress, some partial results are known.<sup>14</sup>

It is known that the Casimir energy produced by integrating out bulk fields for a toroidal bulk have the desired size. More generally, integrating out heavy bulk particles at one loop tends not to cause problems because these loops know about the full 6D supersymmetry of the action. It is the 6D supersymmetry which is relevant to integrating out the dangerous frequencies,  $\omega \gtrsim M_w$ , even though 6D SUSY is broken by the background geometry. This is because these dangerous modes probe very short distances in the bulk, and so are largely insensitive to the geometry over scales  $\sim r$  (as they would have to be to ‘know’ that supersymmetry breaks).

In some circumstances integrating out massive brane fields also need not be dangerous, despite supersymmetry being badly broken on the branes. This is because a sufficient condition for 4D flatness is the absence of a brane coupling to the bulk dilaton, and arbitrary numbers of brane loops cannot generate a coupling to the dilaton if it is not already present at the classical level.

The potentially most dangerous contributions are those which mix brane and bulk loops, since these can introduce couplings between the brane and the dilaton and can know about supersymmetry breaking. The good news here is that it is sufficient to establish that these contributions are small to a small number of loops in the bulk, because the very large size of the extra dimension implies the bulk loops cost a factor of order  $1/r^2$ . (Recall that the observations require a 4D energy density of order  $\mu^4 \sim 1/r^4$ .) It is these calculations of naturalness on which the success or failure of the SLED proposal must ultimately be judged.

## 3 Some Objections

It is useful to close by listing some of the best objections which have been raised against the SLED proposal over the years, together with a cartoon of the arguments as to why they do not (yet) appear to be show-stoppers.

### Why isn’t SLED killed by the arguments against 5D self-tuning?

The observation that higher dimensions can allow 4D flat geometry to coexist with nonzero brane tension was explored<sup>6</sup> and rejected<sup>25</sup> within a 5D context. Given the similarity in their motivations it is natural to wonder if the 6D proposal can be killed in a similar way.

The objection in the 5D case argued that hidden fine-tunings were involved, because the presence of a brane with positive tension,  $T_1$ , necessarily warps the transverse dimensions and forces the bulk geometry to have a singularity elsewhere in the bulk. This singularity is naturally interpreted as the presence of a second brane, and on general grounds this second brane is found to have a negative tension,  $T_2$ , with 4D flatness requiring a cancellation between  $T_1$  and  $T_2$ . How could this cancellation possibly survive integrating out heavy physics on only one brane?

The analogue of this 5D argument arises for 4D-flat compactifications of 6D supergravity on a torus. In this case using  $R_2 = \chi = 0$  in eq. (2) implies  $\sum_b T_b = 0$ , which shows that all such compactifications require cancellation amongst brane tensions. But crucially eq. (2) does *not* rely on 4D flatness. Rather, being topological it must continue to hold under any continuous perturbation, such as the ‘integrating out’ of short-wavelength physics. If, in particular, the tension is adjusted on only one brane then eq. (2) remains true, and implies the bulk geometry must necessarily curve in response. A real calculation is required to see whether the observed 4 dimensions also curve.

### What about Weinberg’s Theorem?

Weinberg has a general no-go theorem<sup>3</sup> against approaches to the CC problem (like SLED) which rely on spontaneously broken classical scale invariance. In a nutshell, this states that scale invariance by itself cannot protect the CC from quantum corrections, even in the absence of scale anomalies. As discussed in more detail elsewhere,<sup>12</sup> as applied to SLED Weinberg’s argument correctly implies that the scale-invariant classical flat direction of 6D supergravity must be lifted by quantum corrections. It does not in itself say *how big* these corrections must be. In SLED this lifting is partially protected by the unusually small bulk-supersymmetry breaking scale,  $\Delta m_s^2 \sim 1/r^2$ , and so must vanish as  $r \rightarrow \infty$ . The key work in progress for SLED is showing that this suppression is of order  $1/r^4$  (in the Jordan frame) rather than merely being of order  $M_w^4$  or  $M_w^2/r^2$ . (Notice that although  $M_w^2/r^2$  is too large to be consistent with the observed Dark Energy, it is parameterically small compared with the normal size,  $O(M_w^4)$ , usually obtained within models.)

### What is the 4D relaxation mechanism for Self-Tuning?

This objection argues against the possibility of ‘self-tuning’, *i.e.* of there being any system for which perturbations of initially 4D-flat solutions lead to new static 4D flat solutions. It arises in the following two different forms:<sup>a</sup>

*Volume Stabilization and Self-Tuning:* One form of the argument argues that eventually it is necessary to stabilize the extra dimensions, and so develop a minimum for some sufficiently large value of  $r \sim r_0$ , with an effective 4D potential satisfying  $V(r_0) \lesssim 1/r_0^4$ . Once this is done, self-tuning would require the potential to adjust dynamically to any changes of microscopic parameters (such as a phase transition on one of the branes) in such a way as to obtain a new stabilized minimum at  $r \sim r'_0$ , with  $r'_0 \sim r_0$  and  $V(r'_0) \lesssim 1/r_0^4$ . But there is no known way to do this within a 4D effective description.

While this seems to be a true statement, SLED is *not* a self-tuning system. At the classical level this can be seen because of its flat direction: any classical perturbation stimulates a roll along the flat direction and so is not attracted towards a new static solution. Furthermore, this property can survive the lifting of the flat direction by quantum corrections, because the resulting  $1/r^4$  potential typically does not stabilize the volume, and also favours a runaway along the would-be flat direction. At the 4D level the low-energy dynamics is described by a

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<sup>a</sup>We thank N. Arkani-Hamed, G.Dvali and J.Polchinski for arguments along these lines.

scalar-tensor theory, with the  $1/r^4$  potential naturally giving a scalar mass of order the Hubble scale:  $m \sim H \sim \mu^2/M_p$ .

What is remarkable is that a light scalar with a potential of the form obtained by dimensional reduction can potentially provide a description of what is seen in cosmology. To see how this might work, imagine that the classical flat direction along which  $r$  can change (parameterizing the classical scale invariance of the 6D equations) is lifted by quantum effects that are of order  $1/r^4$  (which of course is the hard part, see above). Such a potential drives a runaway out to  $r \rightarrow \infty$ , without stabilizing at any fixed  $r$ . However, the full quantum contributions to the potential generically also include logarithms:  $V(r) \sim (1/r^4)[a + b \log r + \dots]$ . It happens that this kind of potential can describe a successful quintessence-type cosmology,<sup>26</sup> with potential domination occurring when<sup>19</sup>  $\log r \sim a/b$ . Of course the success of this cosmology requires finding a compactification for which  $a/b \sim 60$  (which is not yet done); that the universe starts off with somewhat special initial conditions (which we expect in any case from the 6D point of view); and that the light scalar which results is not ruled out by tests of gravity (also possible – but not generic – given the  $\log r$  corrections to its matter couplings<sup>19</sup>). But these are all issues which are likely to be easier to solve than is the original cosmological constant problem.<sup>b</sup>

*Adiabatic Version:* An alternative version of this argument starts from the observation that there is nothing in a low-energy effective theory which precludes having a CC which is larger than the cutoff, provided that it is turned on in a sufficiently adiabatic way. As applied to extra dimensional models, this appears to mean that a CC larger than  $1/r^4$  could make sense in the effective 4D theory designed to describe physics at scales  $E \ll 1/r$ . This argues that extra dimensions *cannot* be key to the argument, since it should be possible to understand purely in four dimensions why one cannot add a large CC compared with the present-day Kaluza-Klein (KK) scale.

The loophole in this argument lies in its ignoring of the scale invariance of the higher-dimensional models, which preclude having a strictly constant term in the low-energy potential. Rather, any large energy density must really arise in the low-energy theory as a potential for  $r$ , of the form  $M^{4-n}/r^n$ . However, for canonically normalized fields,  $\omega \sim M_p \log(Mr)$ , this becomes  $Ae^{\lambda\omega/M_p}$ , for some  $\lambda$ , with  $A \sim M^4$  large. However, besides providing a large energy density, such a term also acts as a force pushing  $\omega$ , implying in particular  $\dot{\omega}^2 \sim M^4$ . Since this implies  $\dot{\omega}$  is greater than the KK scale, it is necessarily non-adiabatic and so not describable purely within the 4D theory.

## 4 Summary

Applying extra dimensions to the cosmological constant problem is clearly a work in progress. However the stakes are high and include the validity of naturalness as a fundamental theoretical criterion. On the one hand extra dimensions are attractive, inasmuch as they break the basic link between vacuum energy and 4D curvature which is at the root of the CC problem. On the other hand, it is not yet known whether loop corrections can be as small as a truly natural solution to the CC problem would require (although this should be known very soon).

Moreover, even if extra dimensions provide stability under renormalization, they inevitably appear to involve special choices of initial conditions if they are to describe our present-day universe. Whether this is a reasonable trade-off, or involves throwing out the baby with the bathwater, can only be decided by examining extra dimensional solutions in more detail.

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<sup>b</sup>An alternative possibility<sup>20</sup> has the coefficient,  $A(r)$ , of the kinetic term,  $A(r)(\partial r)^2$ , vanishing for  $r \sim r_0$ .

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